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SUPERSYMMETRIC DECAYS OF THE TOP QUARK: AN UPDATE *

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ABSTRACT

We analyze the two decays $t \to H^+ b$, $t \to \widetilde{u}_1 \widetilde{\chi}^0_1$ within the Minimal Supersymmetric Standard Model with radiative breaking of the electroweak sector. We discuss their detectability at present and in the eventuality that supersymmetry is not discovered at LEPII.

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ABSTRACT

We analyze the two decays $t \to H^+ b$, $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$ within the Minimal Supersymmetric Standard Model with radiative breaking of the electroweak sector. We discuss their detectability at present and in the eventuality that supersymmetry is not discovered at LEPII.

1. Problem and Inputs

It is well known that in supersymmetric models the top quark can decay at the tree-level into a charged Higgs plus a bottom quark, $t \to H^+ b$, and into a stop $\widetilde{u}_1$ plus the lightest neutralino $\widetilde{\chi}_1^0$, $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$ (see for example [1] and references therein). Both decays can have sizable rates: $t \to H^+ b$ can easily reach the $10-30\%$ level for large $\tan\beta$; $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$ has similarly large rates in some corners of the supersymmetric parameter space [1].

The agreement between the top production cross section measuread at the TEVATRON [2] and that which is predicted by the Standard Model (SM) still allows such large rates. Moreover, the measurement of the top mass (M_t) based on electron and muon tagging is not sensitive to these decay modes. For very large values of $\tan\beta$ which give large $t \to H^+ b$ rates, H^+ decays into third generation leptons $\tau\nu_\tau$ (more than 95% of the times), whereas, in general, the decay into the lightest chargino ($\widetilde{\chi}_2^+$) and neutralino, $H^+ \to \widetilde{\chi}_2^+ \widetilde{\chi}_1^0$, may dominate. In the second mode $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$, $\widetilde{u}_1$ can decay as $\widetilde{u}_1 \to \widetilde{\chi}_2^+ b$ and $\widetilde{u}_1 \to c\widetilde{\chi}_1^0$. In all these channels, a larger amount of missing energy than in the standard $t \to W^+ b$ is produced, which leads to softer spectra for the charged leptons.

By phase space suppression, the abovementioned rates can be progressively reduced to the level of "rare" ones when the masses of H^+, $\widetilde{u}_1$, and $\widetilde{\chi}_1^0$ increase. The question to be answered, therefore, is whether the Minimal Supersymmetric Standard Model (MSSM) can still support these two decay channels (and at which level), once all constraints coming from experiments are imposed. Independently, one should also consider how much information can be extracted for possible extensions of the MSSM by the observation (or non-observation) of these decay modes. In this contribution we provide an answer only to the first of these two questions.

The MSSM studied here is the most minimal realization of a supersymmetric version of the SM, with breaking of the electro-weak sector radiatively induced. We assume that the universal boundary conditions are given near the grand-unified scale of $M_G \sim 3 \cdot 10^{16}$ GeV. We do not make any assumptions regarding the details of the physics at the grand scale and we do not assume $b-\tau$ unification, which is affected by these details [4]. We fix the QCD coupling constant to its average value $\alpha_s(M_Z) = 0.12$ and the running mass

$m_b(M_Z)$ to be $m_b(M_Z) = 3\,\mathrm{GeV}$.

We include radiative corrections to the Higgs potential following the procedure described in [5] while we impose radiative breaking of the electroweak sector. We find that the spectrum of the Higgs mass parameters calculated using one-loop renormalization group equations and tree-level sum rules is slightly heavier than that which is described in [1, 7] where these corrections were not included.

Furthermore, we evaluate the mass–shifts for H^+ induced by these corrections as in [6]. We compare these results with those obtained following other calculations which make use, as [6], of the diagrammatic approch [9] and of the effective potential method [8, 10]. We find, in general, a rather good agreement (after replacing h_b with $-h_b$ in (5d) and (5e) of [10]). In generic supersymmetric models these mass corrections can be large for large left-right mixings in the squark mass matrices and can be positive and negative (this last possibility is in general observed for small values of $\tan\beta$). In our MSSM simulation, however, after radiative breaking of the electroweak sector is imposed, we find that the corrected masses hardly deviate from those obtained using the tree-level sum rules.

We come now to discuss the cuts imposed to the region of parameter space which we study. It is known that the decay $b \to c\tau\nu$ restricts the ratio $r = \tan\beta\,(\mathrm{GeV})/m_{H^+}$ to be $\lesssim 0.5$ in models containing two Higgs doublets with couplings of type II to the fermions (see [11] and related references therein). Although relevant for models of global realizations of supersymmetry and/or extensions of the MSSM [12], this decay is completely ineffective in our case. As we shall see, the experimental lower bounds on supersymmetric masses and the constraints coming from the requirement of radiative breaking of the electroweak gauge group push already m_{H^+} to be larger than $\tan\beta$ (in GeV).

Similarly, the combined limit m_{H^+}–$\tan\beta$ recently set by CDF [3] by measuring energetic jets coming from b-quarks and hadronically decaying τ's (only the mode $H^+ \to \tau^+\nu_\tau$ is considered), does not affect the regions of parameter space which we obtain in our MSSM simulation.

As in [1], also in this analysis, the only effective experimental bounds are those coming from direct searches of supersymmetric particles and from the decay $b \to s\gamma$.

In agreement with results coming from LEP I, LEP1.5 [13], and the TEVATRON, the cuts which we apply to the masses of gluinos $\widetilde{g}$, charginos $\widetilde{\chi}^-$, neutralinos $\widetilde{\chi}^0$, charged and neutral sleptons $\widetilde{l}$, $\widetilde{\nu}$, up- and down-squarks $\widetilde{u}$, $\widetilde{d}$, and neutral Higgses (with h_2^0 the lightest of the two CP-even states, h_3 the CP-odd state and $H^\pm$ the charged Higgs) are (in GeV): $m_{\widetilde{g}} > 150$, $m_{\widetilde{d}_1,\widetilde{u}_2} > 150$, $m_{\widetilde{u}_1} > 45$, $m_{\widetilde{\chi}_2^-} > 60$, $m_{\widetilde{\nu}_1} > 45$, $m_{\widetilde{l}_1} > 45$, $m_{h_2^0} > 45$, $m_{h_3^0} > 20$, $m_{H^\pm} > 45$, $m_{\widetilde{\chi}_1^0} > 20$. For the limit on the mass of the stop-squark we rely on searches at LEP since the decay $\widetilde{u}_1 \to t + \widetilde{\chi}_1^0$ is forbidden or disfavoured at the TEVATRON. The limit on the mass of $\widetilde{\chi}_1^0$, in general higher than the one obtained at LEP, is naturally induced in the MSSM by the limit on the $\widetilde{\chi}_2^-$–mass. Finally, the inclusion of radiative corrections to the Higgs potential and the subsequent modification of the tree-level sum rules for the Higgs-masses force us to impose individual lower bounds for all Higgs particles.

The situation which the Next Linear e^+e^- Collider may have to face if supersymmetric particles remain undiscovered at LEP II can be mimicked by imposing the following

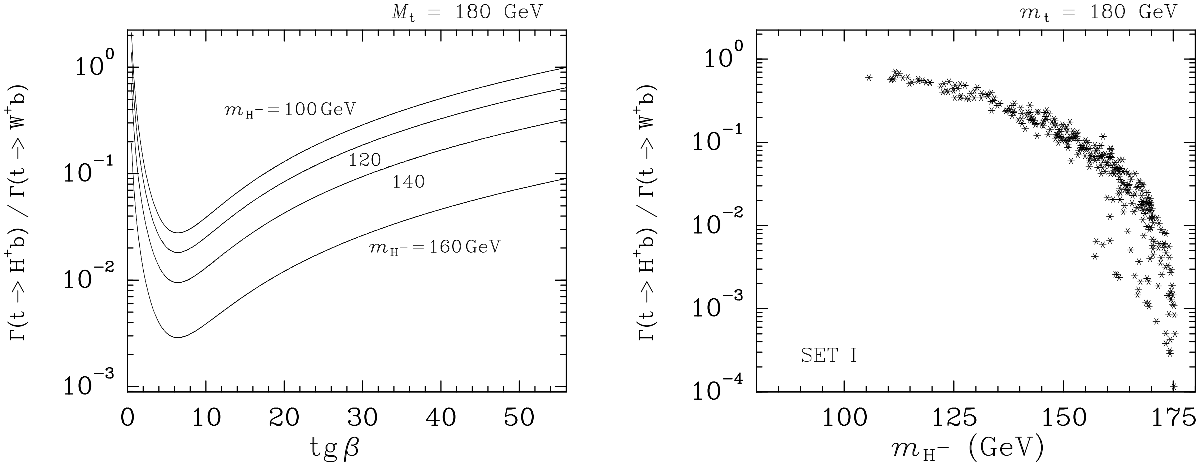

Figure 1: Rates for $t \to H^+b$ in a generic model with SUSY type of Higgs-couplings and in the MSSM

bounds [14] (in GeV): $m_{\widetilde{g}} > 200$, $m_{\widetilde{d}_1,\widetilde{u}_2} > 200$, $m_{\widetilde{u}_1} > 85$, $m_{\widetilde{\chi}_2^-} > 85$, $m_{\widetilde{\nu}_1} > 85$, $m_{\widetilde{l}_1} > 85$, $m_{h_2^0} > 85$, $m_{h_3^0} > 40$, $m_{H^\pm} > 85$, $m_{\widetilde{\chi}_1^0} > 40$. We assume that the TEVATRON limits on squarks and gluino masses will not increase more than 50 GeV. In the following we refer to these two choices of bounds as SET I and SET II.

Finally, we impose the constraints set by the CLEO Collaboration on $b \to s\gamma$: $1 \cdot 10^{-4} < BR(b \to s\gamma) < 4.2 \cdot 10^{-4}$ [15]. The evaluation of $BR(b \to s\gamma)$ is in accordance to [16]; the uncertainty associated to the theoretical prediction (due primarely to the ambiguity in the renormalization scale and to the experimental errors on parameters entering in the calculation) is estimated according to [17].

2. Results: phase spaces and widths

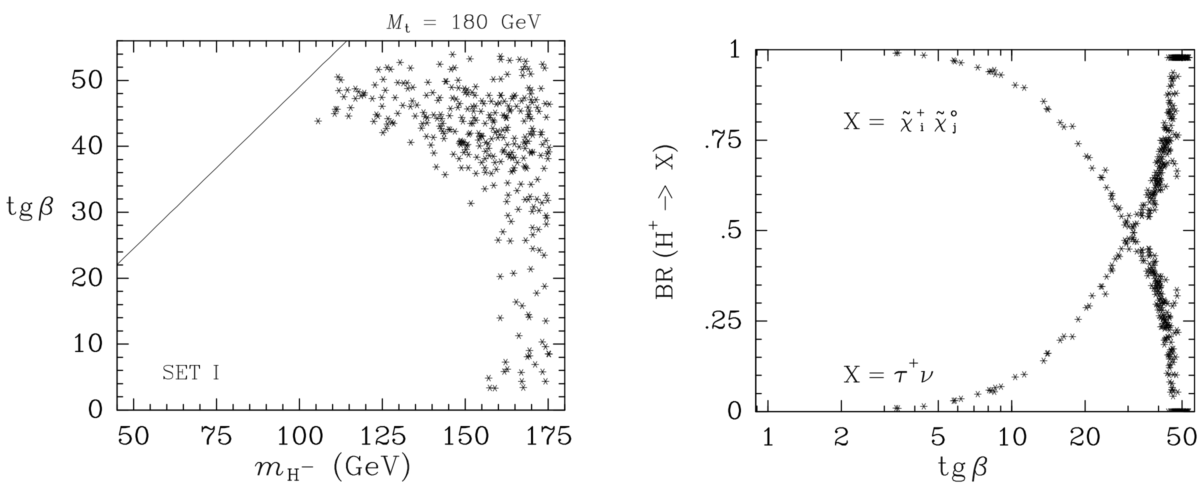

Figure 2: Allowed phase space for $t \to H^+b$ and branching ratios for the decays $H^+ \to \widetilde{\chi}_2^+ \widetilde{\chi}_1^0$, $H^+ \to \tau^+\nu_\tau$

We present in the following the results which we obtain in the MSSM for the two decay modes $t \to H^+b$ and $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$. No QCD or supersymmetric corrections are included

in the calculation of the rates. We show our results separetely before and after imposing the $b \to s\gamma$ constraints.

We show in the first frame of Fig. 1 the m_{H^+} and $\tan\beta$ dependence for the rate $\Gamma(t \to H^+ b)/\Gamma(t \to W^+ b)$ in a model with two Higgs doublets and type II Higgs couplings. The typical minimum for intermediate values of $\tan\beta$ $(3 < \tan\beta < 9)$ is displayed, as well as the following steady increase for increasing $\tan\beta$. The second frame shows the rates obtained in our simulation when the experimental constraints SETI are imposed. The relative phase space for this decay is shown in the first frame of Fig. 2 where, for completeness, we also display the line $\tan\beta(\mathrm{GeV})/m_{H^+} = 0.5$: the region excluded by the decay $b \to c\tau\nu_\tau$ lies above it. The H^+–masses shown in these figures correspond, in general, to values of $|\mu| \sim 150\,\mathrm{GeV}$ and $150 \lesssim |\mu| \lesssim 300\,\mathrm{GeV}$ for $\tan\beta \lesssim 30$.

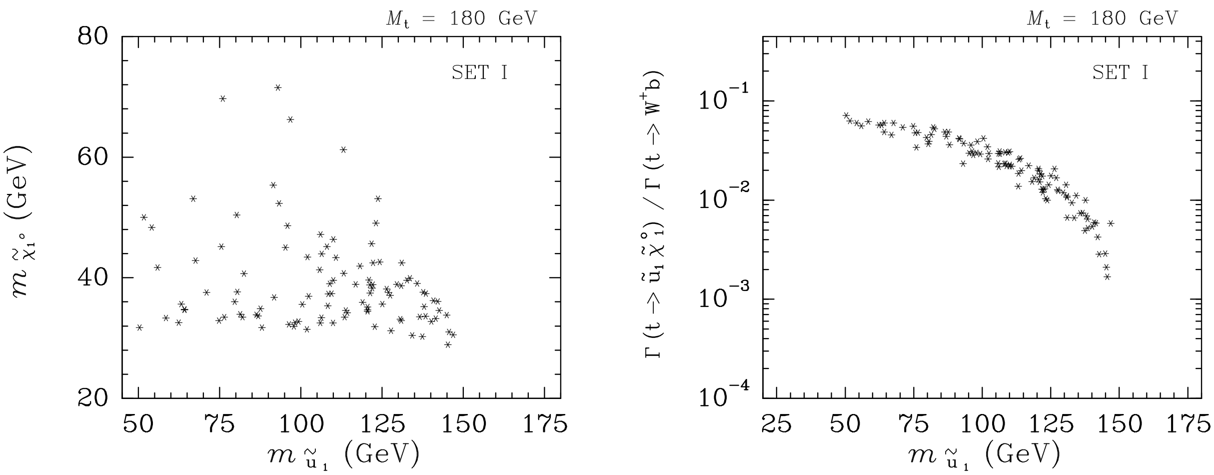

Figure 3: Region of parameter space where $t \to \tilde{u}_1 \tilde{\chi}_1^0$ is kinematically accessible and relative rates

The shape of the phase space obtained has not been drastically affected by the inclusion of radiative corrections to the Higgs potential, with respect to the phase space shown in [1, 7]. The reduction in the size of this area is due to the increase of the experimental lower bounds imposed in this search and to the slightly heavier spectrum of the Higgs–mass parameters used here. As in [1], we find that the largest rates are obtained for the largest values of $\tan\beta$ where also the lightest H^+ are found. The second frame of Fig. 2 shows the branching ratios for the two possible decay modes of the produced H^+. The mode $\tau\nu_\tau$ saturates the total width for H^+ only for very large $\tan\beta$.

Wider regions of the supersymmetric parameter space need to be scanned to obtain the points where the decay $t \to \tilde{u}_1 \tilde{\chi}_1^0$ is kinematically accessible. They correspond to large A and large $|\mu|$ and they are shown in Fig. 3, together with the relative widths. In the lower part of the region, the decay of $\tilde{u}_1$ into an on-shell chargino is still possible. The set of viable points in this figure is disjoint from that where $t \to H^+ b$ is allowed, i.e. the corresponding values of m_{H^+} in the points of Fig. 3 are large, in general above $250\,\mathrm{GeV}$. Therefore, the non-observation of one of the two decay modes, in general, does not affect the possibility of observing the other one.

We show in Fig. 4 what is left for the rates of the two decays once we impose that the

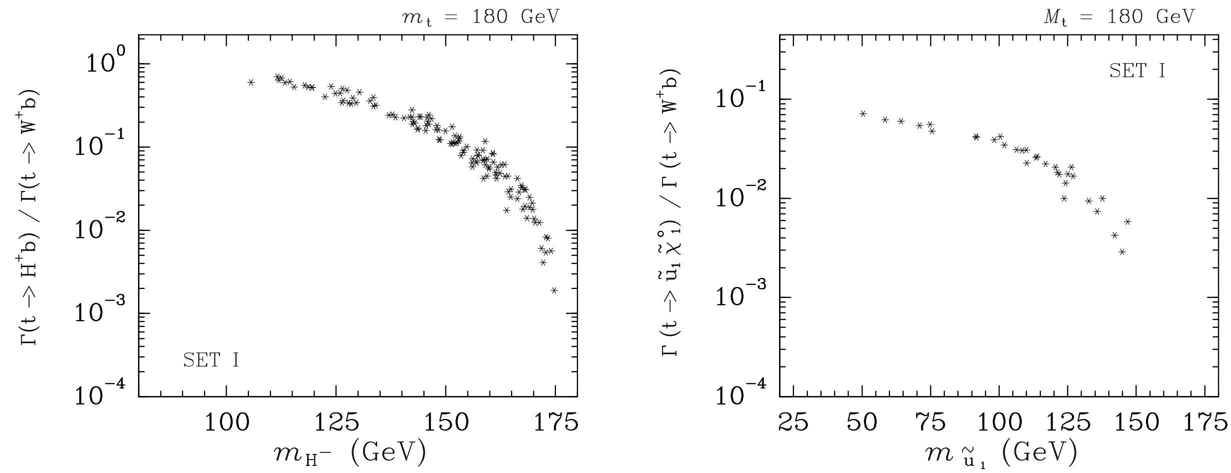

Figure 4: Rates still reachable after the present experimental constraint on $b \to s\gamma$ is imposed

lower theoretical estimate of $BR(b \to s\gamma)$ is $< 4.2 \cdot 10^{-4}$ and that the highest one is $> 1 \cdot 10^{-4}$, for each point of the MSSM parameter space (see for example discussion in [18]). This figure summarizes our prediction for these rates in the MSSM when all experimental constraints existing at present are imposed. We should warn the reader, however, that of the two, the prediction for $t \to H^+ b$ is the most "stable". It does not change very much if the band of allowed values for $b \to s\gamma$ is slightly restricted (see for example the band obtained at 95% c.l. from the measurement $BR(b \to s\gamma) = (2.32 \pm 0.57 \pm 0.35) \cdot 10^{-4}$ [15] when adding statistic and systematic errors in quadrature), whereas the allowed region for $t \to \widetilde{u}_1 \widetilde{\chi}_1^0$ tends to shrink.

Our results for $t \to H^+ b$ are in qualitative agreement with those obtained in [19] where, however, milder lower bounds on supersymmetric particles are imposed.

3. Discussion and Future Prospects

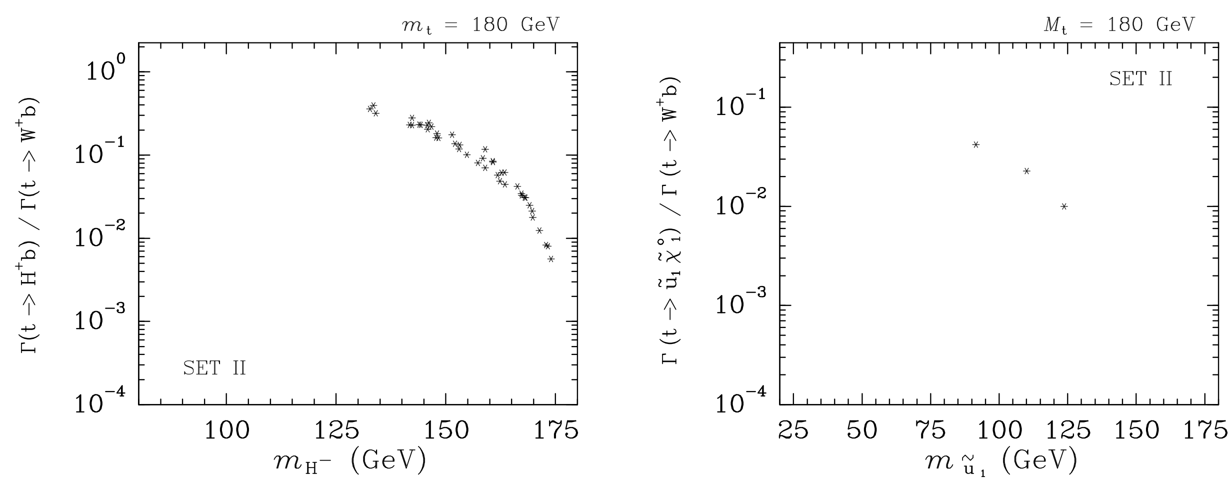

Figure 5: Same as in Fig. 4 when the lower bounds on supersymmetric masses SET II are imposed

As shown in the previous figures, rather large rates for $t \to H^+ b$ can be accomodated

within the MSSM at the moment. The largest values for $\Gamma(t \to H^+b)/\Gamma(t \to \widetilde{u}_1\widetilde{\chi}_1^0)$ may turn out to be excluded in future searches at the TEVATRON. More precision in the experimental measurement and in the theoretical calculation of $BR(b \to s\gamma)$ (through the inclusion of NLO QCD corrections) may completely close the second decay-mode $t \to \widetilde{u}_1\widetilde{\chi}_1^0$. The same effect can be induced by an increase in the lower bounds on supersymmetric masses which LEP II and the TEVATRON will be able to put if no supersymmetric particle are detected in the meantime. We show in Fig. 5 our predictions for the two decays when the lower bounds SET II are imposed, together with the present limit on $b \to s\gamma$.

We conclude noticing that the consequences of the non-observation of $t \to H^+b$ will not be drastic for the MSSM (since the regions of parameter space where $m_{H^+} < M_t$ are indeed not very large), whereas they may turn out to be interesting for models where the strong correlations of the MSSM parameter space are absent.

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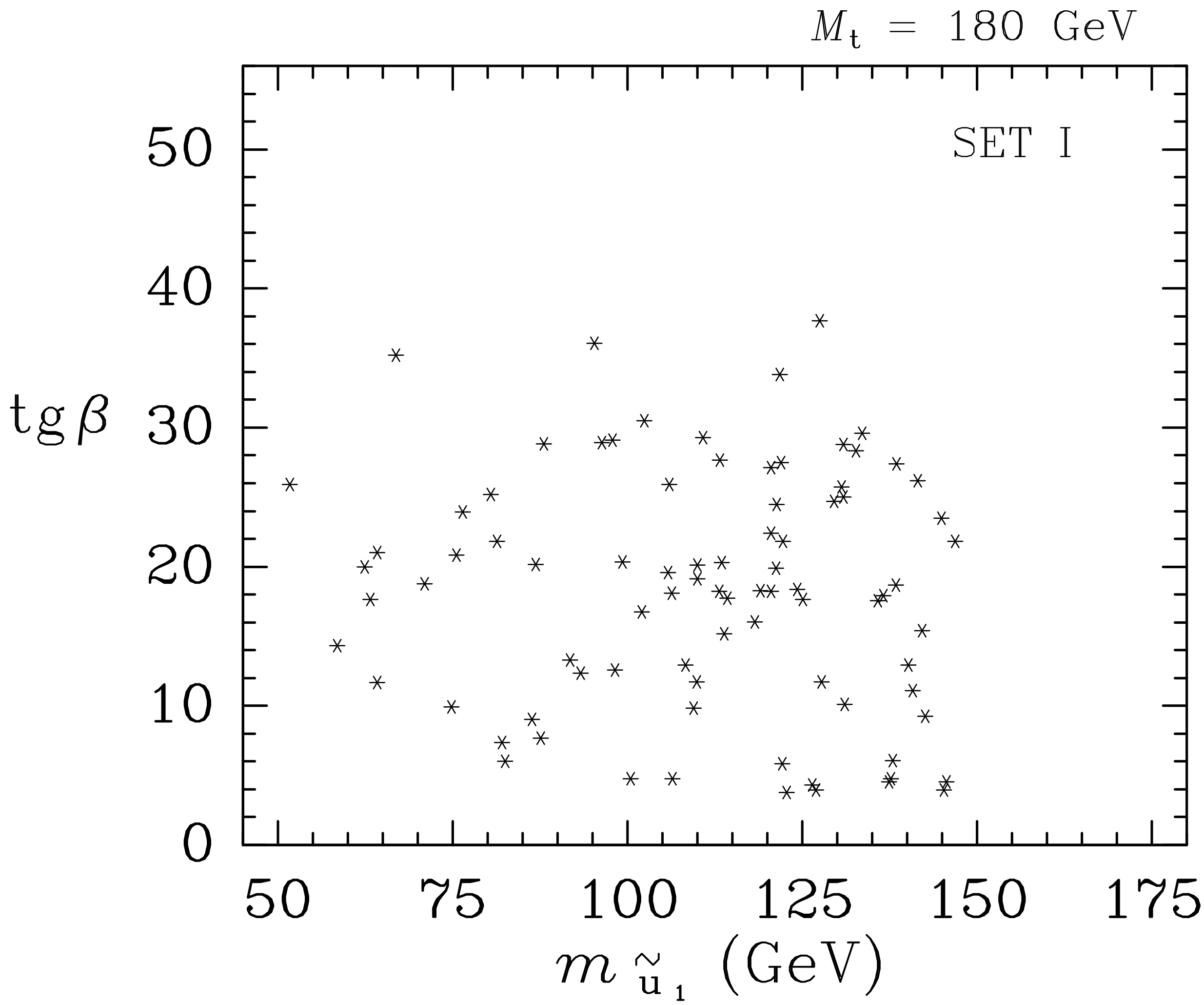
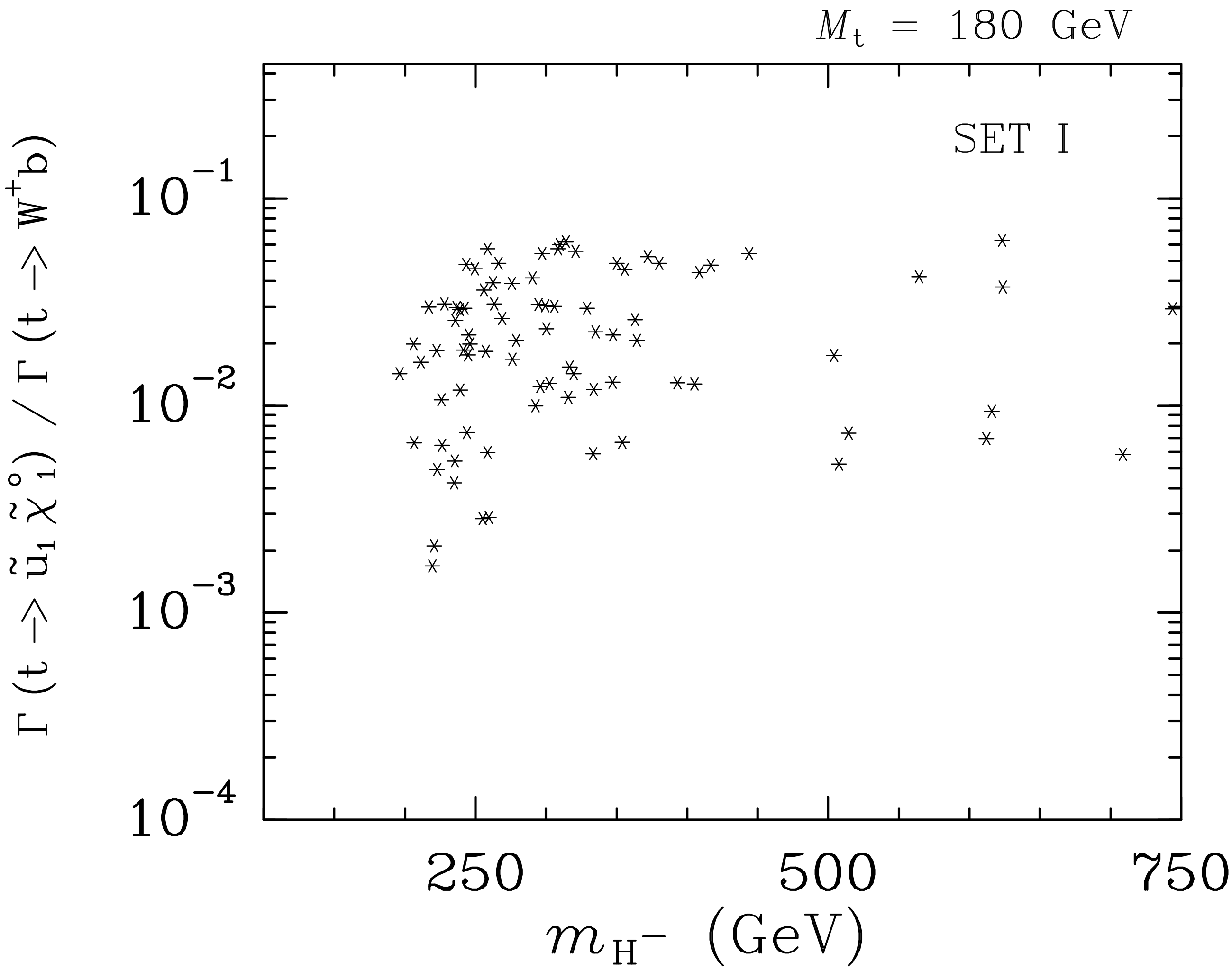
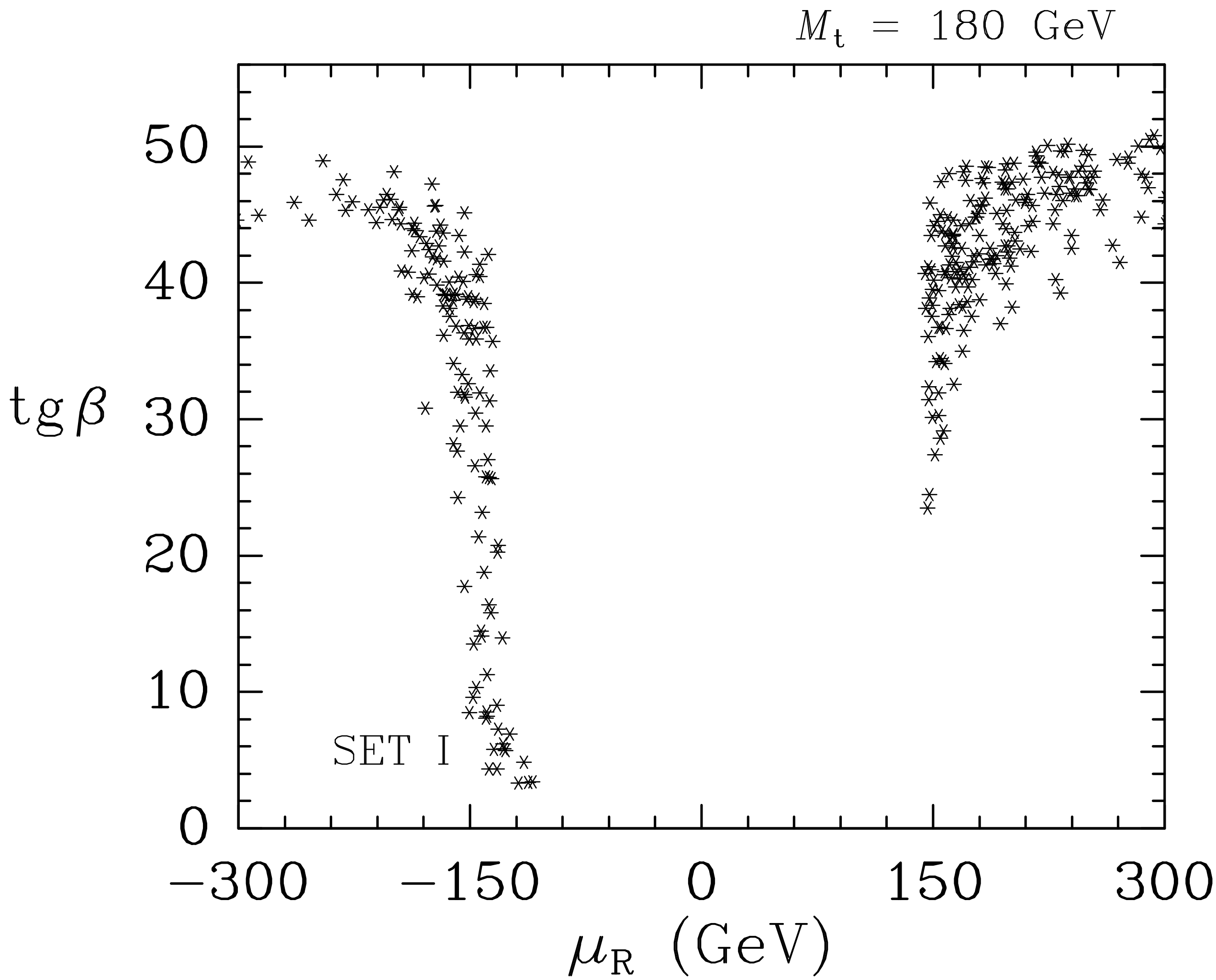


M_t = 180 GeV
SET I
tgβ
$m_{\tilde{u}_1}$ (GeV)
0
10
20
30
40
50
50
75
100
125
150
175



M_t = 180 GeV
SET I
10^{-1}
10^{-2}
10^{-3}
10^{-4}
250
500
750
m_{H^-} (GeV)
$\Gamma(t \to \tilde{u}_1 \tilde{\chi}^\circ_1) \,/\, \Gamma(t \to W^+ b)$



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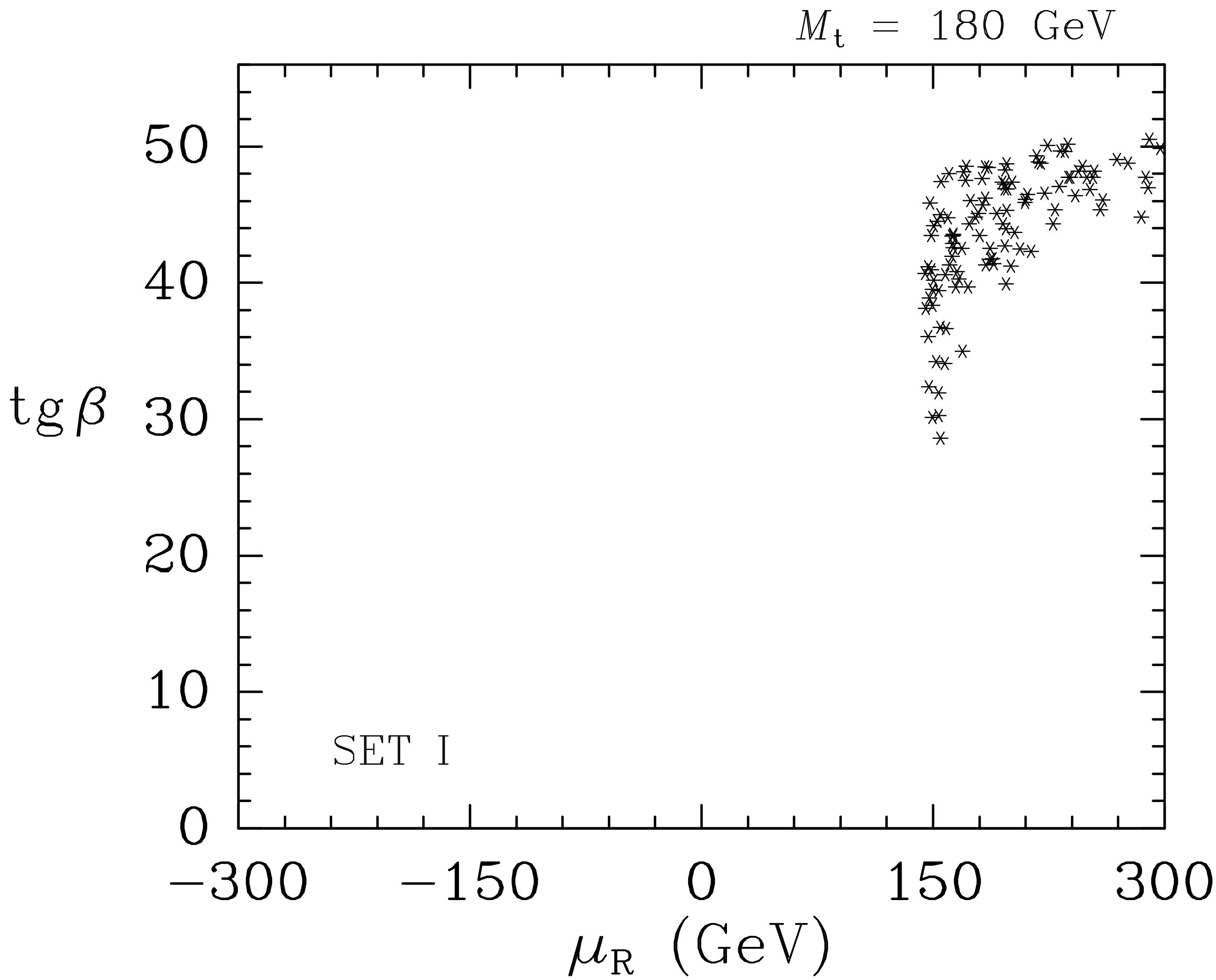
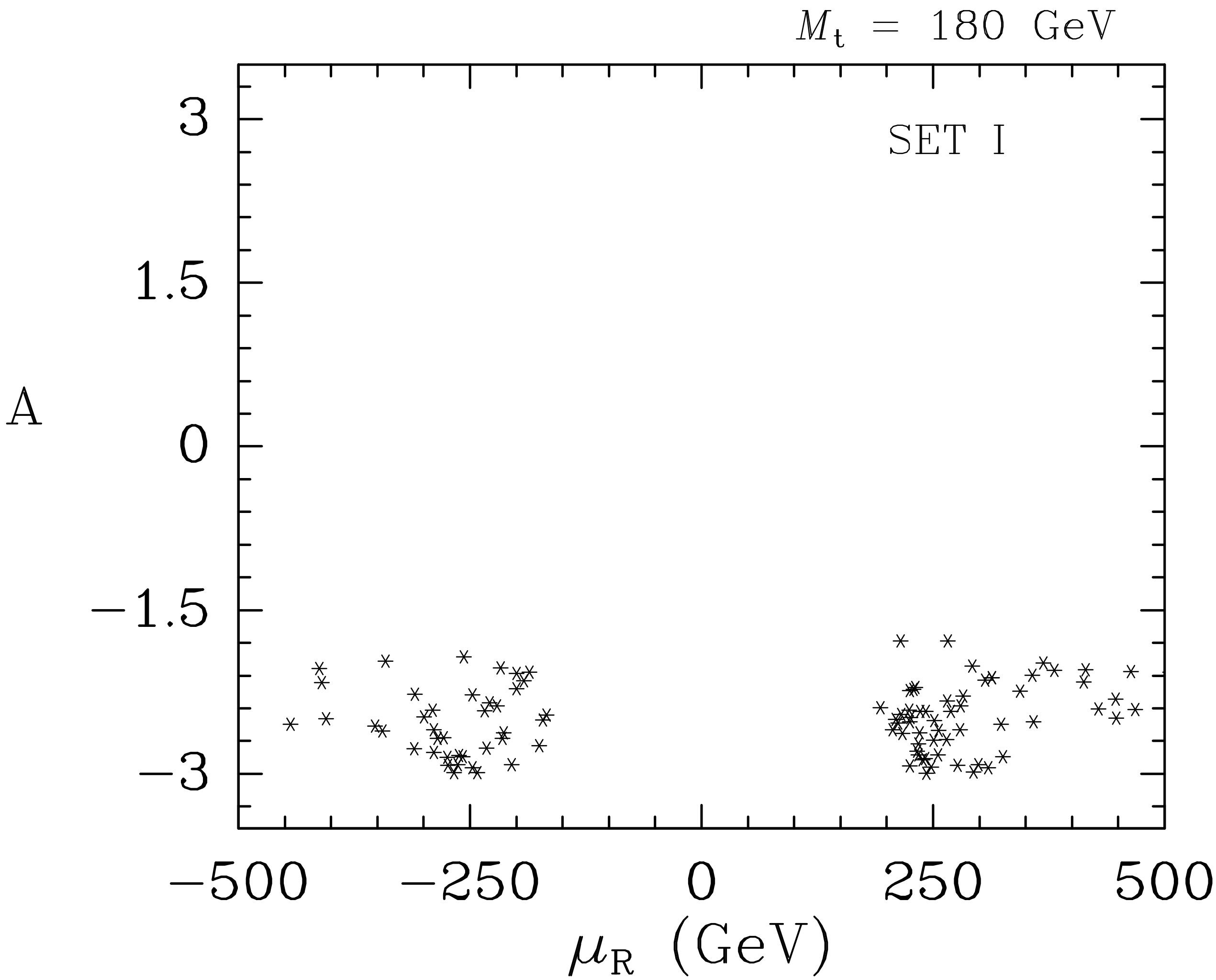
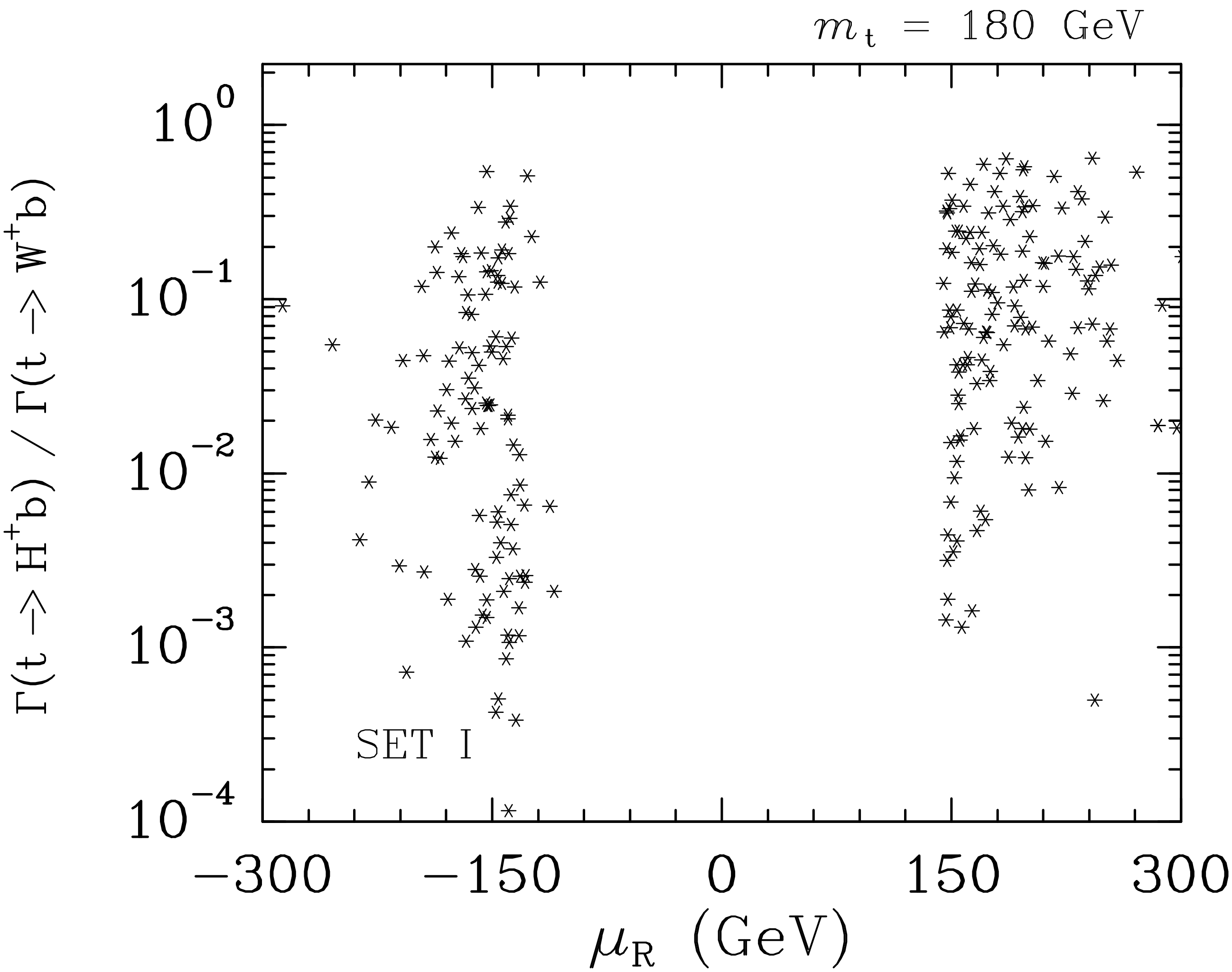
tgβ
μ_R (GeV)
SET I
0
10
20
30
40
50
−300
−150
0
150
300



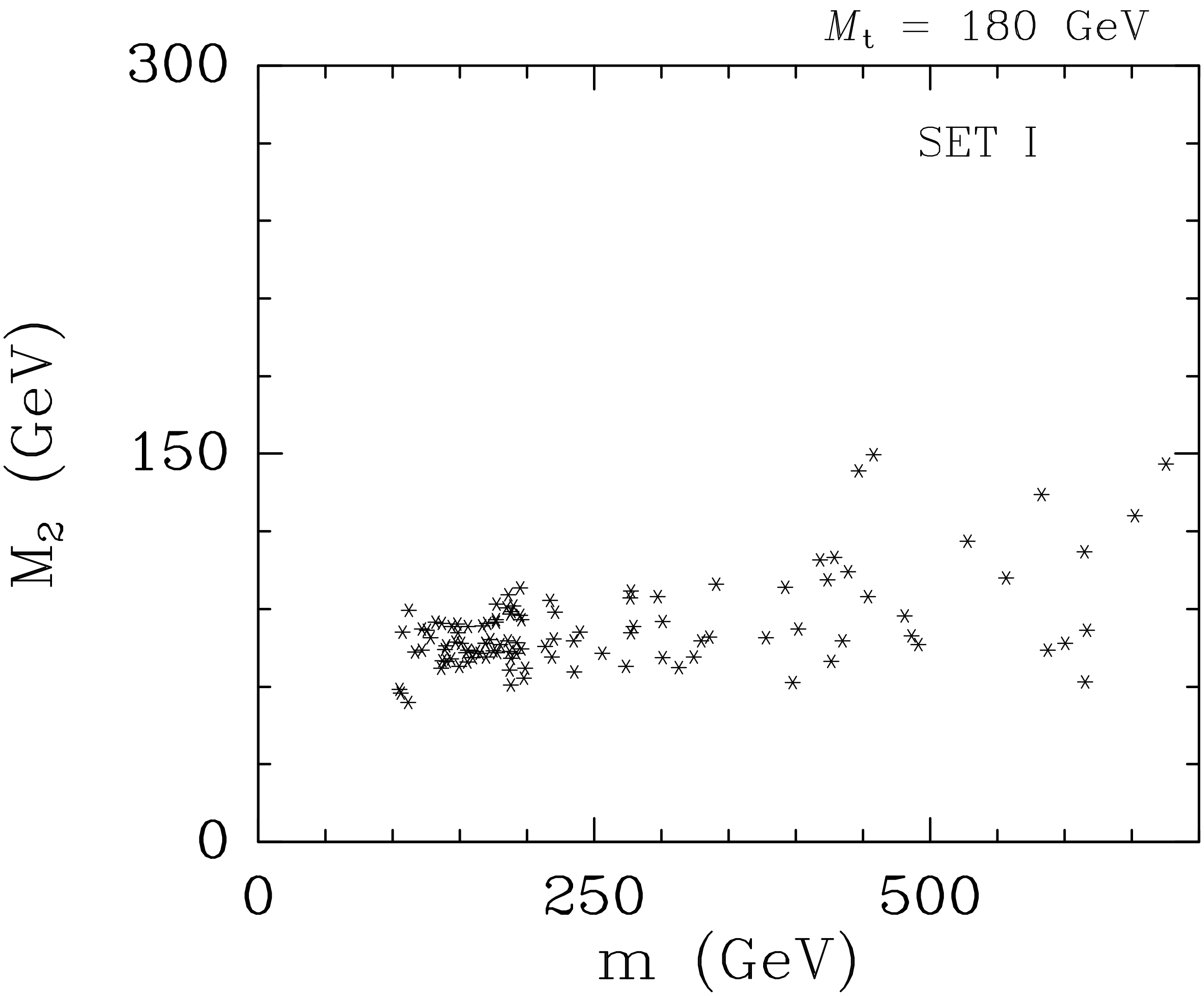
M_t = 180 GeV
tgβ
50
40
30
20
10
0
SET I
−300
−150
0
150
300
μ_R (GeV)



M_t = 180 GeV
SET I
A
3
1.5
0
−1.5
−3
−500
−250
0
250
500
μ_R (GeV)



m_t = 180 GeV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\Gamma(t \to H^+b) / \Gamma(t \to W^+b)$
SET I
−300
−150
0
150
300
μ_R (GeV)



M_t = 180 GeV
SET I
300
150
0
M_2 (GeV)
0
250
500
m (GeV)